CP violation in Higgs @ $\gamma\gamma$ and $\mu\mu$ colliders

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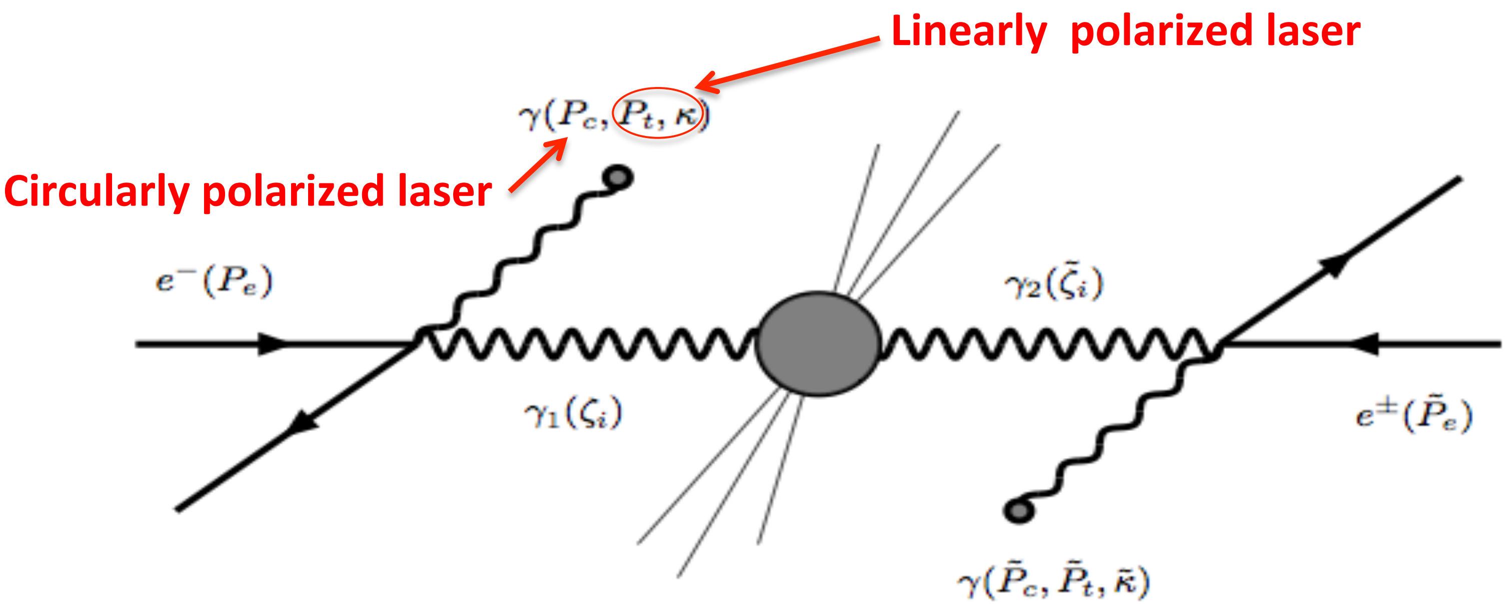
$\gamma\gamma$ Ideal To Measure CP Mixing and Violation

- Well defined CP-states, with *linearly* ($\lambda = 0$) polarized γ's

  $\Rightarrow (\gamma_{\parallel} \parallel \gamma_{\parallel}) \Rightarrow$ CP-even

  $\Rightarrow (\gamma_{\parallel} \perp \gamma_{\parallel}) \Rightarrow$ CP-odd



ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

Only with $\gamma\gamma C$

<u>**In s-channel production of Higgs:**</u>

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2}\left\{[1+\zeta_2\tilde{\zeta}_2] + \mathcal{A}_1\left[\zeta_2+\tilde{\zeta}_2\right] + \mathcal{A}_2\left[\zeta_1\tilde{\zeta}_3+\zeta_3\tilde{\zeta}_1\right] - \mathcal{A}_3\left[\zeta_1\tilde{\zeta}_1-\zeta_3\tilde{\zeta}_3\right]\right\}$$

== 0 if CP is conserved

== +1 (-1) if CP is conserved for A CP-Even (CP-Odd) Higgs

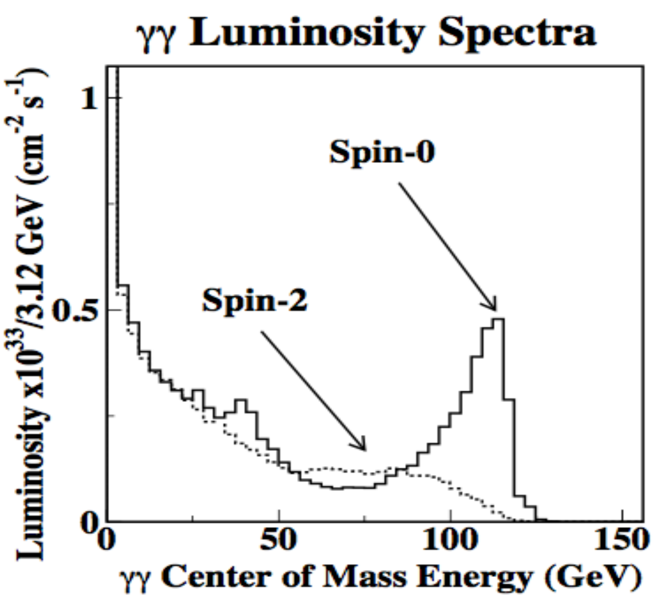
If $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$ and/or $|\mathcal{A}_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

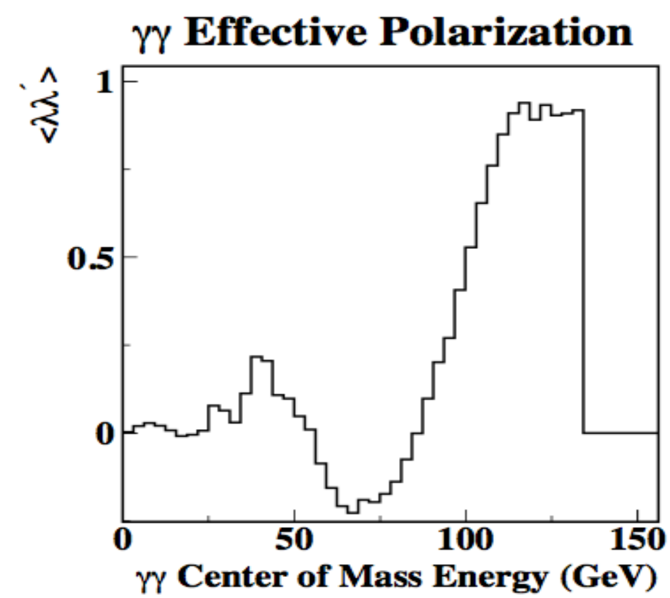
In bb, a ≤1% asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

arXiv:0705.1089v2

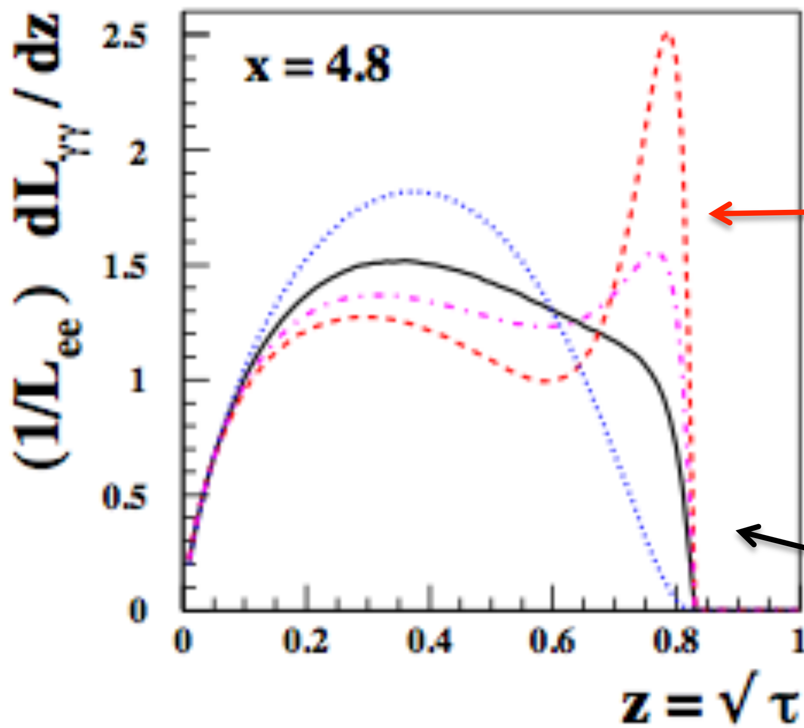
Circularly polarized photons: better S/B than linear polarization case due to the J=2 suppression

- Well defined $J = 0, 2$ final states,
  when starting with *circularly* $(\lambda = \pm 1)$ polarized γ's





Intensity also lower for linearly polarized beams



Used in A_1 measurements (-1,-1)

Used in $A_{2,3}$ measurements (0, 0)

$(P_e \times P_c, \tilde{P}_e \times \tilde{P}_c)$

μμ Collider

Jack Gunion et. al.
SNOWMASS 2001

At a muon collider Higgs factory there is a particularly appealing approach. For resonance, R, production at a MUC with $\overline{\mu}(a + ib\gamma_5)\mu$ coupling to the muon,

$$\begin{aligned} \overline{\sigma}_S(\zeta) &= \overline{\sigma}_S^0 \left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{a^2 - b^2}{a^2 + b^2} \cos\zeta - \frac{2ab}{a^2 + b^2} \sin\zeta\right]\right) \\ &= \overline{\sigma}_S^0 \left[1 + P_L^+ P_L^- + P_T^+ P_T^- \cos(2\delta + \zeta)\right] , \end{aligned} \qquad (2)$$

- $\delta \equiv \tan^{-1} \frac{b}{a}$,
- P_T (P_L) is the degree of transverse (longitudinal) polarization: no $P_T \Rightarrow$ sensitivity to $\overline{\sigma}_S^0 \propto a^2 + b^2$ only.
- ζ = angle of the μ^+ transverse polarization relative to that of the μ^- as measured using the the direction of the μ^-'s momentum as the $\hat{z}$ axis.
- Only the $\sin\zeta$ term is truly CP-violating, but $\cos\zeta$ also $\Rightarrow$ significant sensitivity to a/b.

Ideal = isolate $\frac{a^2-b^2}{a^2+b^2}$ and $\frac{-2ab}{a^2+b^2}$ via the asymmetries (take $P_T^+ = P_T^- \equiv P_T$ and $P_L^\pm = 0$)

a = CP-even, b = CP-odd

CP asymmetries at μμ Collider

$$\mathcal{A}_I \equiv \frac{\overline{\sigma}_S(\zeta=0)-\overline{\sigma}_S(\zeta=\pi)}{\overline{\sigma}_S(\zeta=0)+\overline{\sigma}_S(\zeta=\pi)} = P_T^2\frac{a^2-b^2}{a^2+b^2} = P_T^2\cos 2\delta$$

$$\mathcal{A}_{II} \equiv \frac{\overline{\sigma}_S(\zeta=\pi/2)-\overline{\sigma}_S(\zeta=-\pi/2)}{\overline{\sigma}_S(\zeta=\pi/2)+\overline{\sigma}_S(\zeta=-\pi/2)} = -P_T^2\frac{2ab}{a^2+b^2} = -P_T^2\sin 2\delta$$

A good determination (comparable to LC $\gamma\gamma$) of b and a is possible **if luminosity can be upgraded from SM96 or higher proton source intensity is available.**

→ Need new numbers!

$$\mathcal{A}_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,, \quad \mathcal{A}_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2)\cdot \hat{p}_{\rm beam}$$

Let's not forget the τ's

Techniques based on self-analyzing Higgs decays

To illustrate, consider $h \to \tau^+\tau^-$ and $\tau^\pm \to \pi^\pm\nu$ decays (JFG+Grzadkowski; also Soni and collaborators).
Imagine a general coupling $\overline{\tau}(a + ib\gamma_5)\tau$: $a =$ CP-even, $b =$ CP-odd.

$\Rightarrow$ enough constraints to determine $\pi^\pm$ directions in $\tau^\pm$ rest frames.
Define θ, ϕ and $\overline{\theta}, \overline{\phi}$ as the angles of π^- and π^+ in the τ^- and τ^+ rest frames, respectively, *employing the direction of τ^- in the h rest frame as the coordinate-system-defining z axis.* $\Rightarrow$

$$dN \propto \Big[(b^2 + a^2\beta_\tau^2)(1 + \cos\theta\cos\overline{\theta}) + (b^2 - a^2\beta_\tau^2)\sin\theta\sin\overline{\theta}\cos(\phi - \overline{\phi}) - 2ab\beta_\tau\sin\theta\sin\overline{\theta}\sin(\phi - \overline{\phi})\Big] d\cos\theta\, d\cos\overline{\theta}\, d\phi\, d\overline{\phi}\,, \quad (3)$$

The idea is to use the above dependencies to isolate

$$\rho_1 \equiv \frac{2ab\beta_\tau}{(b^2 + a^2\beta_\tau^2)}, \quad \rho_2 \equiv \frac{(b^2 - a^2\beta_\tau^2)}{(b^2 + a^2\beta_\tau^2)}. \quad (4)$$

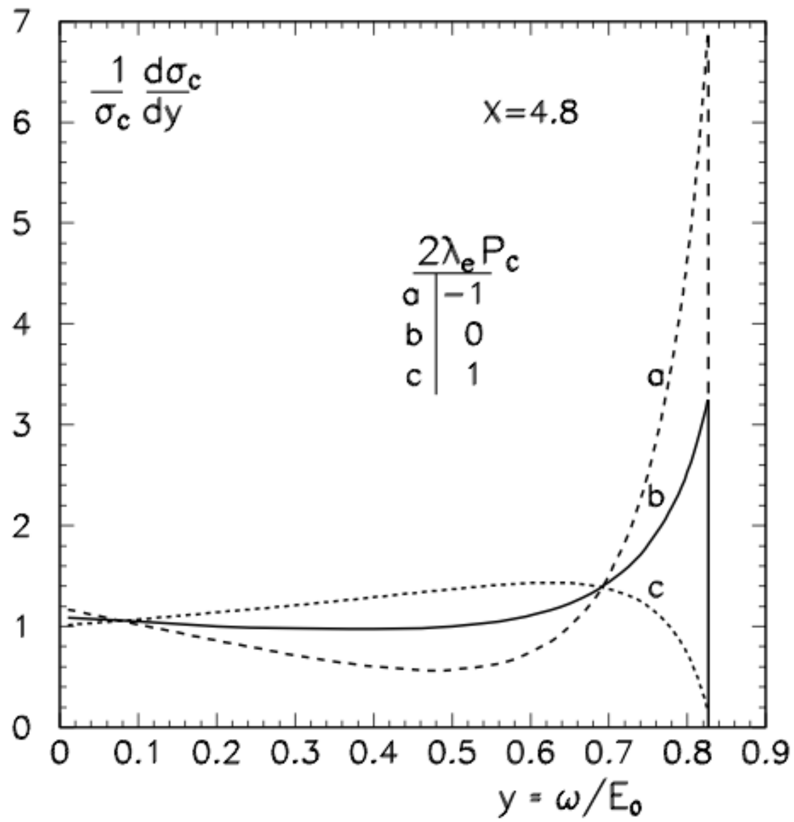
Conclusion

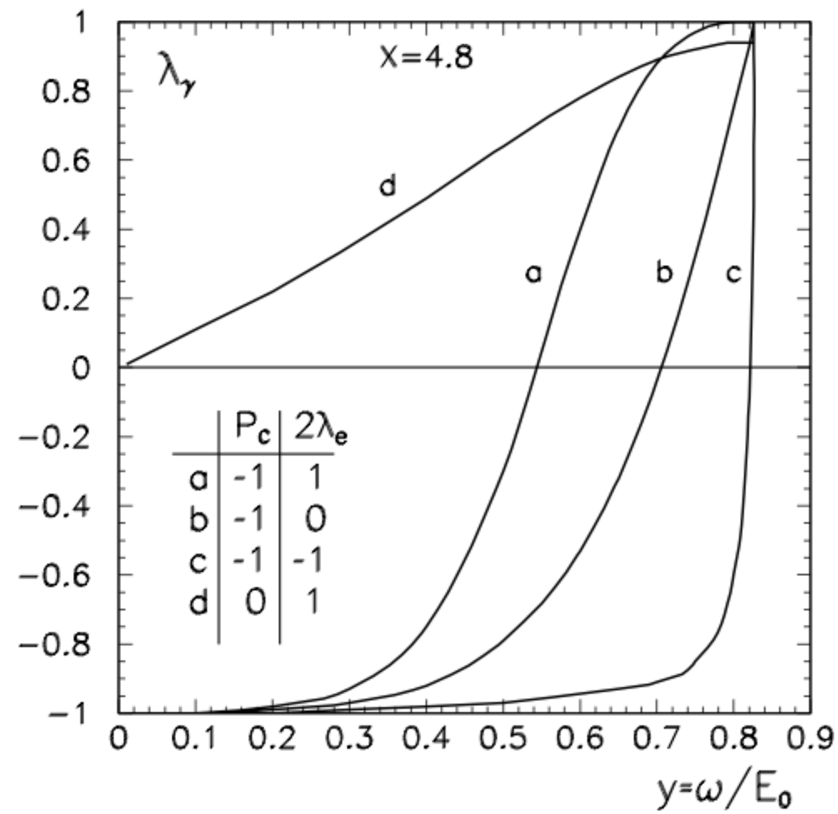
- Circular and Linear polarization of the γ beam in a $\gamma\gamma C$ can be manipulated by just changing the polarization of the γ_{laser}
  - Very powerful tool as we can isolate CP even and CP odd component of the Higgs
  - CP-violating asymmetries using circularly polarized beam can be measured to better than <1% within a year
- Muon Colliders also sensitive to CP asymmetries by manipulating the longitudinal and transverse polarization of the muon beam
  - Clean environment to study CP with τ's

BACKUP

How γ beams are produced

$e^- \gamma_{laser} \rightarrow e^- \gamma$





Linear polarization laser $P_C = 0$

Circular polarization laser $P_C = \pm 1$